The Hydrogen Bomb: II

In which the technical and strategic discussion of last issue is continued, and a proposal is made for a first step toward the international control of atomic weapons

by Hans A. Bethe

LAST month Louis N. Ridenour published an article on the hydrogen bomb in this magazine. The discussion is continued in this second article because of the tremendous importance of the issue. Ridenour described the essential parts of the theory of the nuclear reactions in the hydrogen bomb, and also discussed the likely effects of the bomb on our military security. I agree entirely with his view that the creation of the H-bomb makes our country more vulnerable rather than more secure. It remains for me to discuss two things: On the technical side, I shall try to clarify the many misconceptions that have crept into the discussions of the H-bomb in the daily press. On the political side, I wish to take up the moral issue and the meaning of the bomb in the general framework of our foreign relations.

Everybody who talks about atomic energy knows Albert Einstein's equation $E = Mc^2$; *viz.*, the energy release in a nuclear reaction can be calculated from the decrease in mass. In the fission of the uranium nucleus, one tenth of one per cent of the mass is converted into energy; in the fusion of four hydrogen nuclei to form helium, seven tenths of one per cent is so converted. When these statements are made in newspaper reports, it is usually implied that there ought to be some way in which all the mass of a nucleus could be converted into energy, and that we are merely waiting for technical developments to make this practical. Needless to say, this is wrong. Physics is sufficiently far developed to state that there will never be a way to make a proton or a neutron or any other nucleus simply disappear and convert its entire mass into energy. It is true that there are processes by which various smaller particles—positive and negative electrons and mesons—are annihilated, but all these phenomena involve at least one particle which does not normally occur in nature and therefore must first be created, and this creation process consumes as much energy as is afterwards liberated.

All the nuclear processes from which energy can be obtained involve the rearrangement of protons and neutrons in nuclei, the protons and neutrons themselves remaining intact. Hundreds of experimental investigations through the last 30 years have taught us how much energy can be liberated in each transformation, whether by the fission of heavy nuclei or the fusion of light ones. In the case of fusion, only the combination of the very lightest nuclei can release very large amounts of energy. When four hydrogen nuclei fuse to form helium, .7 per cent of the mass is transformed into energy. But if four helium nuclei were fused into oxygen, the mass would decrease by only .1 per cent; and the fusion of two silicon atoms, if it ever could occur, would release less than .02 per cent of the mass. Thus there is no prospect of using elements of medium atomic weight for the release of nuclear energy, even in theory.

> **EDITOR'S NOTE**
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THE main problem in the release of nuclear energy in those cases that we can consider seriously is not the amount of energy released—this is always large enough—but whether there is a mechanism by which the release can take place at a sufficient rate. This consideration is almost invariably ignored by science reporters, who seem to be incurably fascinated by $E = Mc^2$. In fusion the rate of reaction is governed by entirely different factors from those in fission. Fission takes place when a nucleus of uranium or plutonium captures a neutron. Because the neutron has no electric charge and is not repelled by the nucleus, temperature has no important influence on the fission reaction; no matter how slow the neutron, it can enter a uranium nucleus and cause fission. In fusion reactions, on the other hand, two nuclei, both with positive electric charges, must come into contact. To overcome their strong mutual electrical repulsion, the nuclei must move at each other with great speed. Ridenour explained how this is achieved in the laboratory by giving very high velocities to a few nuclei. This method is very ineffi-

cient because it is highly unlikely that one of the fast projectiles will hit a target nucleus before it is slowed down by the many collisions with the electrons also present in the atoms of the target. Therefore the energy released by nuclear reactions in these laboratory experiments is always much less than the energy invested in accelerating the particles.

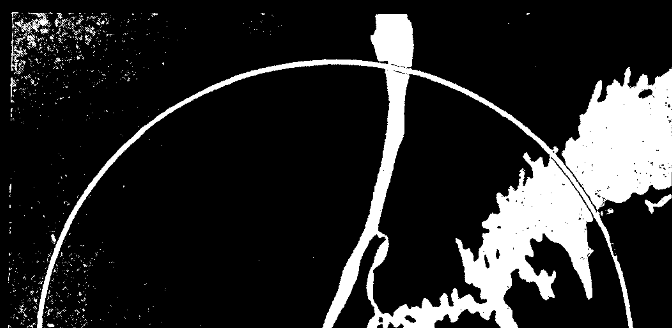
The only known way that energy can be extracted from light nuclei by fusion is by thermonuclear reactions, *i.e.*, those which proceed at exceedingly high temperatures. The prime example of such reactions occurs in the interior of stars, where temperatures are of the order of 20 million degrees Centigrade. At this temperature the average energy of an atom is still only 1,700 electron volts—much less than the energies given to nuclear particles in "atom smashers." But all the particles present—nuclei and electrons—have high kinetic energy, so they are not slowed down by colliding with one another. They will keep their high speeds. Nevertheless, in spite of the high temperature, the nuclear reactions in stars proceed at an extremely slow rate; only one per cent of the hydrogen in the sun is transformed into helium in a billion years. Indeed, it would be catastrophic for the star if the reaction went much faster.

The temperature at the center of a star is kept high and very nearly constant by an interplay of a number of physical forces. The radiation produced by nuclear reactions in the interior can escape from the star only with great difficulty. It proceeds to the surface not in a straight line but by a complicated, zigzag route, since it is constantly absorbed by atoms and re-emitted in new directions. It is this slow escape of radiation that maintains the high interior temperature, which in turn maintains the thermonuclear reactions. Only a star large enough to hold its radiations for a long time can produce significant amounts of energy. The sun's radiation, for example, takes about 10,000 years to escape. A star weighing one tenth as much as the sun would produce so little energy that it would not be visible, and the largest planet, Jupiter, is already so small that it could not maintain nuclear reactions at all. This rules out the possibility that the earth's atmosphere, or the ocean, or the earth's crust, could be set "on fire" by a hydrogen superbomb and the earth thus be converted into a star. Because of the small mass of the bomb, it would heat only a small volume of the earth or its atmosphere, and even if nuclear reactions were started, radiation would carry away the nuclear energy much faster than it developed, and the temperature would drop rapidly so that the nuclear reaction would soon stop.

If thermonuclear reactions are to be initiated on earth, one must take into consideration that any nuclear energy released will be carried away rapidly by radiation, so that it will not be possible to keep the temperature high for a long time. Therefore, if the reaction is to proceed at all, it must proceed very quickly. Reaction times of billions of years, like those in the sun, would never lead to an appreciable energy release; we must think rather in terms of millionths of a second. On the other hand, on earth we have a choice of materials: whereas the stellar reactions can use only the elements that happen to be abundant in stars, notably ordinary hydrogen, we can choose any elements we like for our thermonuclear reactions. We shall obviously choose those with the highest reaction rates.

The reaction rate depends first of all, and extremely sensitively, on the product of the charges of the reacting nuclei; the smaller this product, the higher the reaction rate. The highest rates will therefore be obtainable from a reaction between two hydrogen nuclei, because hydrogen has the smallest possible charge —one unit. (The principal reactions in

BLAST EFFECT of present and proposed atomic weapons is projected on a map of New York City and the surrounding area. A uranium bomb set off above the SCIENTIFIC AMERICAN office in midtown would cause severe destruction within a radius of a mile (*small circle*); a hydrogen bomb 1,000 times more powerful would cause severe destruction within 10 miles (*large circle*).



FLASH EFFECT of a hydrogen bomb 1,000 times more powerful than present bombs would be relatively greater than its blast effect. The Hiroshima bomb caused fatal burns at distances up to 4,000 to 5,000 feet (*small circle*). A hydrogen bomb would cause fatal burns at distances of 20 miles or more (*large circle*). The inhabitants of Chicago and its suburbs could thus be wiped out.

$H^1 + H^1 \longrightarrow H^2 + e^+$	1.4 mev	100,000,000,000 years
$H^2 + H^1 \longrightarrow He^3 + h\nu$	5 mev	.5 second
$H^3 + H^1 \longrightarrow He^4 + h\nu$	20 mev	.05 second
$H^2 + H^2 \longrightarrow He^3 + n$	3.2 mev	.00003 second
$H^2 + H^2 \longrightarrow H^3 + H^1$	4 mev	.00003 second
$H^3 + H^2 \longrightarrow He^4 + n$	17 mev	.0000012 second
$H^3 + H^3 \longrightarrow He^4 + n + n$	11 mev	?

THE NUCLEAR REACTIONS involving the three isotopes of hydrogen, H^1, H^2 (deuterium) and H^3 (tritium) illustrate a fundamental consideration in making a hydrogen bomb. The reactions are at left, the energy released by each is in center, the time required for each is at right. The reactions involving the heavier isotopes of hydrogen proceed at a much faster rate.

stars are between carbon, of charge six, and hydrogen.) We can choose any of the three hydrogen isotopes, of atomic weight one (proton), two (deuteron) or three (triton). These isotopes undergo different types of nuclear reactions, and the reactions occur at different rates.

The fusion of two protons is called the proton-proton reaction. It has long been known that this reaction is exceedingly slow. As Robert E. Marshak stated in his article, "The Energy of Stars," in the January issue of this magazine, the proton-proton reaction takes 100 billion years to occur at the center of the sun. Ridenour pointed out that the situation is quite different for the reactions using only the heavy isotopes of hydrogen: the deuteron and triton. A number of reported measurements by nuclear physicists have shown that the reaction rates for this type of fusion are high.

A further variable governing the rate of the reaction is the density of the material. The more atoms there are per unit volume, the higher the probability for nuclear collisions.

It is also well known, as Ridenour noted, that the reactions would require enormous temperatures. Whether the temperature necessary to heat heavy hydrogen sufficiently to start a thermonuclear reaction can be achieved on the earth is a major problem in the development of the H-bomb. To find a practical way of initiating H-bombs will require much research and considerable time.

WHAT would be the effects of a hydrogen bomb? Ridenour pointed out that its power would be limited only by the amount of heavy hydrogen that could be carried in the bomb. A bomb carried by a submarine, for instance, could be much more powerful than one carried by a plane. Let us assume an H-bomb releasing 1,000 times as much energy as the Hiroshima bomb. The radius of destruction by blast from a bomb increases as the cube root of the increase in the bomb's power. At Hiroshima the radius of severe destruction was one mile. So an H-bomb would cause almost complete destruction of buildings up to a radius of 10 miles. By the blast effect alone a single bomb could obliterate almost all of Greater New York or Moscow or London or any of the largest cities of the world. But this is not all; we must also consider the heat effects. About 30 per cent of the casualties in Hiroshima were caused by flash burns due to the intense burst of heat radiation from the bomb. Fatal burns were frequent up to distances of 4,000 to 5,000 feet. The radius of heat radiation increases with power at a higher rate than that of blast, namely by the square root of the power instead of the cube root. Thus the H-bomb would widen the range of fatal heat by a factor of 30; it would burn

people to death over a radius of up to 20 miles or more. It is too easy to put down or read numbers without understanding them; one must visualize what it would mean if, for instance, Chicago with all its suburbs and most of their inhabitants were wiped out in a single flash.

In addition to blast and heat radiation there are nuclear radiations. Some of these are instantaneous; they are emitted by the exploding bomb itself and may be absorbed by the bodies of persons in the bombed area. Others are delayed; these come from the radioactive nuclei formed as a consequence of the nuclear explosion, and they may be confined to the explosion area or widely dispersed. The bombs, both A and H, emit gamma rays and neutrons while they explode. Either of these radiations can enter the body and cause death or radiation sickness. It is likely, however, that most of the people who would get a lethal dose of radiation from the H-bomb would be killed in any case by flash burn or by collapsing or burning buildings.

There would also be persistent radioactivity. This is of two kinds: the fission products formed in the bomb itself, and the radioactive atoms formed in the environment by the neutrons emitted from the bomb. Since the H-bomb must be triggered by an A-bomb, it will produce at least as many fission products as an A-bomb alone. The neutrons produced by the fusion reactions may greatly increase the radioactive effect. They would be absorbed by the bomb case, by rocks and other material on the ground, and by the air. The bomb case could be so designed that it would become highly radioactive when disintegrated by the explosion. These radioactive atoms would then be carried by the wind over a large area of the bombed country. The radioactive nuclei formed on the ground would contaminate the center of the bombed area for some time, but probably not for very long because the constituents of soil and buildings do not form many long-lived radioactive nuclei by neutron capture.

Neutrons released in the air are finally captured by nitrogen nuclei, which are thereby transformed into radioactive carbon 14. This isotope, however, has a long half-life—5,000 years—and therefore its radioactivity is relatively weak. Consequently even if many bombs were exploded, it is not likely that the carbon 14 would become dangerous.

THE decision to proceed with the development of hydrogen bombs has been made. I believe that this decision settles only one question and raises a hundred in its place. What will the bomb do to our strategic position? Will it restore to us the superiority in armament that we possessed before the Russians obtained the A-bomb? Will it improve our chances of winning the next war if one should come? Will it diminish the likelihood that we should see our cities destroyed in that war? Will it serve to avert or postpone war itself? How will the world look after a war fought with hydrogen bombs?

I believe the most important question is the moral one: Can we who have always insisted on morality and human decency between nations as well as inside our own country, introduce this weapon of total annihilation into the world? The usual argument, heard in the frantic week before the President's decision and frequently since, is that we are fighting against a country which denies all the human values we cherish, and that any weapon, however terrible, must be used to prevent that country and its creed from dominating the world. It is argued that it would be better for us to lose our lives than our liberty, and with this view I personally agree. But I believe this is not the choice facing us here; I believe that in a war fought with hydrogen bombs we would lose not only many lives but all our liberties and human values as well.

Whoever wishes to use the hydrogen bomb in our conflict with the U.S.S.R., either as a threat or in actual warfare, is adhering to the old fallacy that the ends justify the means. The fallacy is the more obvious because our conflict with the U.S.S.R. is mainly about means. It is the means that the U.S.S.R. is using, both in dealing with her own citizens and with other nations, that we abhor; we have little quarrel with the professed aim of providing a decent standard of living for all. We would invalidate our cause if we were to use in our fight means that can only be termed mass slaughter.

We believe in personal liberty and human dignity, the value and importance of the individual, sincerity and openness in the dealings between men and between nations, prosperity for all and peace based on mutual trust. All this is in great contrast to the methods which the Soviet Government uses in pursuing its aims and which it believes necessary in the "beginning phase" of Communism —which by now has lasted 33 years. Regimentation of the private lives of all citizens, systematic education in spying upon one's friends, ruthless shifting of populations regardless of their personal ties and preferences, inhuman treatment of prisoners in labor camps, suppression of free speech, falsification of history in dealing both with their own citizens and with other nations, violation of promises and treaties and the distorted interpretations offered in excuse of these violations—these are some of the methods of the U.S.S.R. which are hateful to the people of the Western World. But if we wish to fight against these methods, *our* methods must be clean.

We believe in peace based on mutual trust. Shall we achieve it by using hydrogen bombs? Shall we convince the Russians of the value of the individual by killing millions of them? If we fight a war and win it with H-bombs, what history will remember is not the ideals we were fighting for but the methods we used to accomplish them. These methods will be compared to the warfare of Genghis Khan, who ruthlessly killed every last inhabitant of Persia.

WHAT would an all-out war fought with hydrogen bombs mean? It would mean the obliteration of all large cities and probably of many smaller ones, and the killing of most of their inhabitants. After such a war, nothing that resembled present civilization would remain. The fight for mere survival would dominate everything. The destruction of the cities might set technology back a hundred years or more. In a generation even the knowledge of technology and science might disappear, because there would be no opportunity to practice them. Indeed it is likely that technology and science, having brought such utter misery upon man, would be suspected as works of the devil, and that a new Dark Age would begin on earth.

We know what physical destruction does to the moral values of a people. We have seen how many Germans, already demoralized by the Nazis, lost all sense of morality when during and after the war the bare necessities of life, food, clothing and shelter were lacking. Democracy and human decency were empty words; there was no reserve strength left for such luxuries. If we have learned any lesson from the aftermath of World War II, it is that physical destruction brings moral destruction.

We have also learned that prosperity is the best shield against communism and dictatorship, and in this knowledge we have poured billions into Western Europe to restore her economy. This generosity has won us more friends than anything else we have done. But after the next war, if it were fought with atomic and hydrogen bombs, our own country would be as grievously destroyed as Europe and the U.S.S.R., and we could no longer afford such generosity. It would be everyone for himself, and everyone against the other.

It is ironical that the U. S. of all countries should lead in developing such methods of warfare. The military methods adopted by this nation at the outset of the Second World War had the aim of conserving lives as much as possible. Determined not to repeat the slaughter of the First World War, during which hundreds of thousands of soldiers were sacrificed in fruitless frontal attacks, the U. S. high command substituted war by machines for war by unprotected men. But the hydrogen bomb carries mechanical warfare to ultimate absurdity in

defeating its own aim. Instead of saving lives, it takes many more lives; in place of one soldier who would die in battle, it kills a hundred noncombatant civilians. Surely it is time for us to reconsider what our real intentions are.

One may well ask: Why advance such arguments with reference to the H-bomb and not atomic bombs in general? Is an atomic bomb moral and a hydrogen bomb immoral, and if so, where is the dividing line? I believe there was a deep feeling in this country right after the war that the use of atomic bombs in Japan had been a mistake, and that these bombs should be eliminated from national armaments. This feeling, indeed, was one of the prime reasons for President Truman's offer of international control in 1945. We know that the negotiations for control have not led to success as yet. But our inability to eliminate atomic bombs is no reason to introduce a bomb which is a thousand times worse.

When atomic bombs were first introduced, there was a general feeling that they represented something new, that the thousandfold increase of destructive power from blockbuster to atom bomb required and made possible a new approach. The step from atomic to hydrogen bombs is just as great again, so we have again an equally strong reason to seek a new approach. We have to think how we can save humanity from this ultimate disaster. And we must break the habit, which seems to have taken hold of this nation, of considering every weapon as just another piece of machinery and a fair means to win our struggle with the U.S.S.R.

I HAVE reviewed the moral issues that should deter us from using hydrogen bombs even if we were sure that we alone would have them, and that they would contribute to our victory. As Ridenour explained, the situation is rather the opposite. We can hardly expect to have a monopoly on hydrogen bombs. If we ever had any illusions about this, the events of the past few months should have destroyed them. The U.S.S.R. has the atomic bomb. She was undoubtedly helped in her efforts by the secret information she received from Klaus Fuchs, which presumably included many of the vital "secrets" of our project. But knowing how a group of scientists put the bomb together would not by itself enable a nation to make one. If Fuchs had given his information to Spain, for instance, it would hardly have been understood; it would presumably not have been used, and even if used it would almost certainly not have led to success. The prime requirements for the job still are a group of highly capable scientists, a country determined to make the weapon and a great industrial effort. We know now, if we ever doubted it, that the U.S.S.R. has all of these. For the Soviet scientists the information must simply have resolved many doubts as to which steps to take next and saved a number of costly and futile parallel developments.

Their obvious competence will presumably again bring success to the Russians when they try to develop the H-bomb. Yet their decisions and their successes are not independent of our own. Our decision to make the H-bomb, which showed that we considered the project feasible, may well have prompted them to take the same decision. For this reason I think that our decision, if taken at all, should have been taken in secret. This became impossible, however, when the advocates of the H-bomb used public statements as a means of exerting pressure on the President. If the Russians were already working on the H-bomb before our decision, they will now have increased their effort.

It is impossible to predict whether we or the Russians will have the hydrogen bomb first. We like to assume that we shall. If so, I refuse to believe that the U. S. would start a preventive war. That would violate all the fundamental beliefs of this nation, and that these beliefs are still strong is shown by the history of the past four years: although we had a monopoly of the atomic bomb we did not start a war. Clearly, then, the time will come when both the U.S.S.R. and this country will have H-bombs. Then this country will be much more vulnerable than the U.S.S.R.: as Ridenour explained, we have many more large cities that would be inviting targets, and many of these lie near the coast so that they could be reached by submarine and perhaps a relatively short-range rocket. I think it is therefore correct to say that the existence of the hydrogen bomb will give us military weakness rather than strength.

BUT, say the advocates of the bomb, what if the Russians obtain the H-bomb first? If the Russians have the bomb, Harold Urey argued in a speech just before the President's decision, they may confront us with an ultimatum to surrender. I do not believe we would accept such an ultimatum even if we did not have the H-bomb, or that we would need to. I doubt that the hydrogen bomb, dreadful as it would be, could win a war in one stroke. Though it might devastate our cities and cripple our ability to conduct a long war with all modern weapons, it would not seriously affect our power for immediate retaliation. Our atomic bombs, whether "old style" or hydrogen, and our planes would presumably be so distributed that they could not all be wiped out at the same time; they would still be ready to take off and reduce the country of the aggressor to at least the same state as our own. Thus the large bomb would bring untold destruction but no decision. I believe that "old-fashioned" A-bombs would be sufficient to even the score in case of an initial Soviet attack with H-bombs on this country. In fact, because of the greater number available, A-bombs may well be more effective in destroying legitimate military targets, including production centers. H-bombs, after all, would be useful only against the largest targets, of which there are very few in the U.S.S.R.

So we come finally to one reason, and only one, that can justify our building the H-bomb: namely, to deter the Russians from using it against us, if only for fear of our retaliation. Our possession of the bomb might possibly put us in a better position if the U.S.S.R. should present us with an ultimatum based on their possession of it. In other words, the one purpose of our development of the bomb would be to prevent its use, not to use it.

If this is our reason, we can contribute much to the peace of the world by stating this reason openly. This could be done in a declaration, either by Congress or by the President, that the U. S. will never be the first to use the hydrogen bomb, that we would employ the weapon only if it were used against us or one of our allies. A pledge of this kind was proposed in a press statement by 12 physicists, including myself, on February 4. It still appears to me as a practical step toward relief of the international tension, and toward freedom from fear for the world. The pledge would indicate our desire to avoid needless destruction; it would reduce the likelihood of the use of the hydrogen bomb in the case of war, and it would largely eliminate the danger that fear of the H-bomb itself would precipitate a war.

If we do not make this pledge, the hydrogen bomb would almost surely be used. Once war broke out, our military leaders would be blamed, in the absence of a pledge, if they did not immediately initiate a full-scale hydrogen-bomb attack. But if such a pledge existed, they would be blamed if they did use the bomb first. To be sure, the pledge might not be relied on by our adversaries, but at least it would create a doubt in their minds and they might decide to wait and see. Perhaps they would not wish to provoke the certain use of the bomb by dropping the first one. Moreover, if they started a war, they would probably hope to capture our country and to exploit its wealth rather than to conquer a heap of rubble.

We have proposed unilateral action rather than an international treaty on this pledge. We have done this because negotiations with the U.S.S.R. are known to be long and frustrating. A unilateral pledge involving only this country could be made quickly, and it could not again lead to the disappointment of a break-

down of negotiations. On the other hand, we certainly would not want to exclude a pact with the U.S.S.R. on this subject. This might be the first point on which the two countries could agree, and this in itself would be important.

Obviously the pledge can only be a first step. What we really want is a workable agreement on atomic energy, as part of our efforts toward a lasting peace. Much has been said in the last few weeks about new negotiations on atomic control. Opinions vary from that of Senator Brien McMahon, who proposed to spend $50 billion for rehabilitation of war-devastated countries including the U.S.S.R. in exchange for an atomic settlement, to that of Senator Millard Tydings, who declared that an atomic settlement would not be acceptable to this country unless it was coupled with general disarmament, which he has advocated for a long time. Both of these viewpoints, and those of many other Senators, show the desire of this country for some agreement. At the same time there are persistent reports, clearly indicated in recent dispatches from the New York *Times* correspondent in Moscow, that the Russians might like to negotiate. It seems to me that too much is at stake to miss any such opportunity.

ON the other hand, President Truman voiced the fears of many of us when he stated recently that there is no security in agreements with the Russians because they break them at will. He referred to the agreements of Yalta and Potsdam in 1945. Since then we have learned much about Soviet methods, and the Russians have found that we do not retreat as easily as they apparently imagined in 1945. This more realistic mutual appraisal makes it much more likely that we could now come to arrangements which neither side would regret afterward. Obviously in any negotiation each side must be willing to make concessions and to consider primarily proposals directed to mutual advantage rather than superiority over the other.

The situation in atomic energy has changed, both because of the Soviet development of the A-bomb and because of our decision on the H-bomb. To leave atomic weapons uncontrolled would be against the best interests of both countries. If we can negotiate seriously with the U.S.S.R., the scope of the negotiations should probably be as broad as possible. But the situation would be greatly eased even if we could agree only to eliminate the greatest menace to civilization, the hydrogen bomb.

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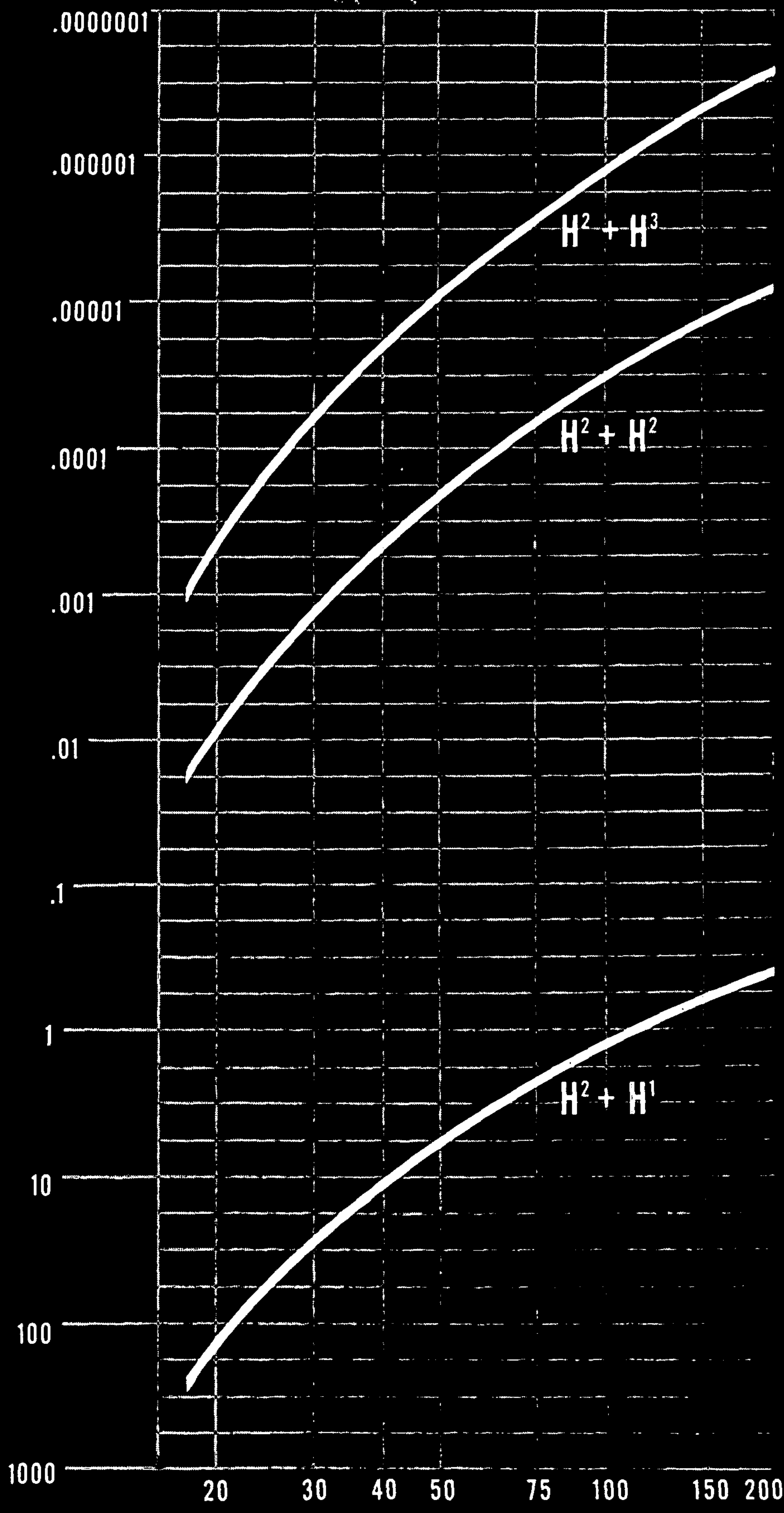

THE TIME REQUIRED for the nuclear reactions between deuterons (H^2 nuclei) and each of the three hydrogen isotopes is plotted against temperature. The vertical coordinate is in seconds; the horizontal coordinate in millions of degrees Centigrade. Deuteron-triton reaction proceeds fastest. Sun's temperature is 6,000 degrees at surface, 20 million degrees at center.